METHOD AND APPARATUS FOR CONTROLLING EXHAUST EMISSIONS FROM A COMPRESSION-IGNITION ENGINE

TECHNICAL FIELD

This invention pertains generally to internal combustion engine control systems, and more specifically to a system to control exhaust emissions from a compression-ignition engine.

BACKGROUND OF THE INVENTION

There is a continuing need for engine manufacturers to improve exhaust emissions from compression-ignition ('CI') engines to meet government regulations and to improve customer satisfaction. The challenges for meeting emissions regulations for CI engines tend to focus on meeting requirements for nitrides of oxygen ('NOx') emissions because the CI engines typically operate lean of stoichiometry, where NOx emissions are primarily generated. Current CI engines are typically unable to run at stoichiometry or rich of stoichiometry under medium or high load conditions, due in part to combustion chamber designs.

Engine manufacturers have implemented exhaust aftertreatment devices to meet increasingly stringent emissions regulations. Typical exhaust aftertreatment devices may comprise several different aftertreatment elements including, for example, oxidation catalysts, NOx adsorber catalysts, and diesel particulate filters. The exhaust aftertreatment elements are typically comprised of ceramic substrates including washcoats that are operable to accomplish exhaust aftertreatment functions, as described by their associated names. The design and placement of the various exhaust aftertreatment elements in the exhaust system depend upon the regulatory requirements and customer expectations a particular engine is intended to meet.

One specific exhaust aftertreatment device is the NOx adsorber catalyst,

which is operable to selectively store NOx emissions during lean engine operation. A compression-ignition engine typically operates lean of stoichiometry to derive various benefits, including improved fuel economy. The NOx adsorber catalyst is typically comprised of a ceramic substrate coated with a washcoat containing barium, salts such as potassium or sodium, and other materials. The washcoat formulation is developed based upon an operating temperature range of the engine's exhaust gas feedstream, as determined over the range of engine operation. By way of example, a NOx adsorber intended for operation on a medium or heavy-duty truck is designed to operate most effectively in a temperature window between 250° C and 550° C. The NOx adsorber catalyst is operable to store, or adsorb NOx emissions during lean engine operation. The NOx adsorber has a finite capacity to store NOx emissions, and the capacity is affected by the NOx adsorber operating temperature and the exhaust gas feedstream from the engine. If the operating temperature is outside the operating temperature range, the NOx storage capacity of the NOx adsorber typically drops significantly. The NOx adsorber catalyst must be purged periodically to prevent increased emissions, which results from saturation of the NOx adsorber and a breakthrough of NOx emissions. The control system of the compression-ignition engine acts to purge NOx emissions by periodically shifting engine control to operate at stoichiometry, or rich of stoichiometry. Alternatively, a compression-ignition engine and control system may periodically inject reductants into the exhaust feedstream to shift the exhaust gas feedstream to rich of stoichiometry to purge the NOx adsorber catalyst. A more detailed description of exhaust aftertreatment systems for use with compression-ignition engines may be found in a technical paper by Dou and Balland (SAE Paper 2002-01-0734) entitled *Impact of Alkali Metals on the Performance and Mechanical Properties of NOx Adsorber Catalysts*.

When engine control is shifted to operate at stoichiometry, or rich of stoichiometry, the NOx adsorber desorbs, or purges NOx. The NOx adsorber

and other aftertreatment devices then convert the NOx to nitrogen and other elements. Performance of the NOx adsorber is typically measured in terms of a NOx efficiency rating, which is linked to the aforementioned cycle of adsorption and desorption. Under normal operating conditions, NOx adsorber efficiency levels may exceed 90%. This helps ensure that a compression-ignition engine with a properly designed aftertreatment system meets emissions requirements. When the engine is at a high load, high speed operating point, the exhaust gas feedstream may be at a temperature that is outside the temperature window described previously. When the engine is at a low load, low speed operating point, the exhaust gas feedstream may also be at a temperature that is outside the temperature window described previously. Prolonged engine operation at conditions leading to high exhaust aftertreatment temperatures may reduce the ability of the engine to meet more stringent emissions regulations over the life of the engine. What is needed is a system and method to effectively meet future emissions requirements for compression-ignition engines, including high temperature operation, using a combination of engine controls and exhaust aftertreatment systems.

SUMMARY OF THE INVENTION

The present invention provides an improvement over conventional engine controls for compression-ignition engines with exhaust aftertreatment systems in that it provides a method and a control system to control exhaust emissions by controlling the operating temperature of the exhaust aftertreatment device. Temperature may be controlled to avoid exceeding a predetermined temperature. The invention includes monitoring operation of the compression-ignition engine, by monitoring engine fuel delivery and engine speed. The temperature of the exhaust aftertreatment device is determined, based upon the monitored operation of the compression-ignition engine and exhaust aftertreatment system. An operating point of the engine is controlled, based upon the determined temperature of the exhaust aftertreatment device. The temperature of the exhaust aftertreatment device is preferably determined using

a temperature sensor in the exhaust aftertreatment system. Determining the temperature of the exhaust aftertreatment device may also include modeling the temperature of the exhaust aftertreatment device based upon input from the temperature sensor or other engine operating parameters, using an algorithm internal to the controller to accurately predict the temperature. The engine operating point is preferably controlled by controlling fuel delivery to the engine from a plurality of fuel injectors, based upon the determined temperature of the exhaust aftertreatment device. Reducing the engine operating point by adjusting fuel delivery to the engine reduces the temperature of the exhaust aftertreatment device.

These and other aspects of the invention will become apparent to those skilled in the art upon reading and understanding the following detailed description of the embodiments.

BRIEF DESCRIPTION OF THE DRAWING

The invention may take physical form in certain parts and arrangement of parts, the preferred embodiment of which will be described in detail and illustrated in the accompanying drawings which form a part hereof, and wherein:

Fig. 1 is a schematic diagram of an embodiment of the invention;

Fig. 2 is a flowchart, in accordance with the invention; and,

Fig. 3 is a response data plot, in accordance with the invention.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings, wherein the showings are for the purpose of illustrating an embodiment of the present invention only and not for the purpose of limiting the same, Fig. 1 shows an internal combustion engine 5, control system 10, and exhaust aftertreatment system 22 which has been constructed in accordance with the present invention.

The invention comprises a method and a control system to control exhaust emissions from an internal combustion engine with an exhaust aftertreatment system. The internal combustion engine 5 is a compression-ignition engine that operates primarily lean of stoichiometry, and is used on light-duty, medium-duty, and heavy-duty applications. The engine 5 includes a plurality of cylinders (not shown), and a plurality of fuel injectors 14, wherein each said fuel injector 14 is operable to deliver fuel to one of the plurality of cylinders. There is preferably an exhaust gas recirculation ('EGR') system 18 that is operable to recirculate exhaust gas from the exhaust manifold 26 to the air intake manifold 28 of the engine 5. There is preferably a turbosupercharger 16 mechanized in the exhaust system to provide pressurized air into the intake manifold 28. The air intake manifold 28 preferably has an intake air temperature sensor 20. There is a crank speed sensor 12 that is operable to measure engine crankshaft position and engine rotational speed. There is preferably an accelerator pedal position sensor 32 that is operable to determine an operator demand for power. Other sensors preferably include a coolant temperature sensor 30, and a vehicle speed sensor (not shown), among other sensors. The mechanization of a compression-ignition internal combustion engine is known to one skilled in the art.

Referring again to Fig. 1, the internal combustion engine 5 also includes the exhaust aftertreatment system 22 downstream of the exhaust manifold 26 and the supercharger 16. The aftertreatment system 22 may be comprised of different aftertreatment elements, depending upon various emissions regulations and accompanying requirements the engine is being designed to meet. In this embodiment, the aftertreatment system 22 preferably includes a catalyzed diesel particulate filter 36 in series with a NOx adsorber catalyst 38. An exhaust temperature sensor 40 operable to measure exhaust gas temperature is preferably placed in the aftertreatment system 22, between the catalyzed diesel particulate filter 36 and the NOx adsorber catalyst 38. The exhaust temperature sensor 42 is preferably designed to accurately measure temperature over the range of

operating temperatures of the exhaust aftertreatment system 22, from 100° C to 700° C. The NOx adsorber catalyst 38 preferably comprises a ceramic honeycomb substrate with a washcoat thereon. The washcoat comprises a solution of barium, and salts such as potassium or sodium, and other materials that have been formulated to adsorb and desorb NOx emissions. The diesel particulate filter 36 preferably comprises a ceramic honeycomb substrate with a washcoat thereon. The washcoat preferably comprises a solution of materials that have been formulated to capture particulates. Aftertreatment systems for compression-ignition engines, including diesel particulate filters 36 and NOx adsorber catalysts 38 are known to one skilled in the art.

The controller 10 is preferably an electronic control module comprised of a central processing unit signally electrically connected to volatile and non-volatile memory devices via data buses (not shown). The controller 10 is signally electrically connected to each of the aforementioned engine and exhaust aftertreatment sensors. The controller 10 is also operably connected to output devices, including the plurality of fuel injectors 14, the supercharger 16, and the EGR system 18. The controller 10 collects information from the aforementioned sensors to determine the engine performance parameters and operator demand for power, and controls the output devices using control algorithms and calibrations that are internal to the controller 10. The control algorithms are typically executed during preset loop cycles such that each control algorithm is executed at least once each loop cycle. A loop cycle is typically repeatedly executed each 3, 6, 15, 25 or 100 milliseconds during ongoing engine operation. The engine performance parameters preferably include an engine operating point, which comprises an instantaneous measure of engine output torque, speed, and air/fuel ratio. The controller 10 is operable to determine the operating point of the engine 5 based upon input from the aforementioned engine sensors and the output devices, preferably including the plurality of fuel injectors 14. Use of the controller 10 to control the operation of the internal combustion engine 5 and to determine an engine operating point is

well known to one skilled in the art.

Under typical operating conditions, the compression-ignition engine 5 operates at an air/fuel ratio that is lean of stoichiometry, and engine-out emissions primarily comprise NOx and carbon particulates. The catalyzed diesel particulate filter 36 of the exhaust aftertreatment device 22 is operable to collect the carbon elements, and the NOx adsorber catalyst 38 is operable to adsorb NOx emissions. The NOx adsorber catalyst 38 of this embodiment most effectively operates at temperatures between 250^{O} C and 550^{O} C. The NOx adsorber catalyst 38 is typically evaluated in terms of average NOx conversion efficiency, which comprises a measure of the ability of the to reduce engine-out emissions over a set time period, typically measured over several minutes of engine operation. The average NOx conversion efficiency varies, depending upon operating temperature, T_{ADS}, of the NOx adsorber catalyst 38, ongoing engine operation and the engine operating point; and age, level of deterioration, and level of poisoning of the NOx adsorber catalyst 38. The NOx adsorber catalyst 38 in a well-designed and calibrated engine and warmed-up exhaust aftertreatment system may operate at greater than 90% NOx conversion efficiency in the aforementioned temperature range. When the adsorber operating temperature T_{ADS} is above 550^{O} C, or below 250^{O} C, the efficiency typically drops to levels of 70% or less for this embodiment of the NOx adsorber catalyst 38. This is shown in Fig. 3. The NOx adsorber catalyst 38 must be periodically purged of NOx emissions to prevent saturation and a corresponding increase in exhaust emissions. To purge the NOx adsorber catalyst 38, the controller 10 periodically shifts the engine air/fuel ratio to stoichiometry or slightly rich of stoichiometry. When the air/fuel ratio of the exhaust gas feedstream shifts rich of stoichiometry, the adsorbed NOx emissions are desorbed from the surface of the NOx adsorber catalyst 38 and reduced to nitrogen (N_2) and oxygen (O_2), plus other elements. The controller 10 limits the time for the rich shift in air/fuel ratio to minimize increased fuel consumption caused by rich engine operation. The use of the controller 10 to

shift engine air/fuel ratio, and the adsorption, desorption, and reduction of NOx emissions from the NOx adsorber catalyst 38 are known one skilled in the art.

An engine designer preferably designs and calibrates a compression-ignition engine to operate at exhaust gas temperatures in the range necessary for effective NOx adsorber catalyst efficiency. When the engine operating point is a high speed, high-torque condition, the temperature of the exhaust gas feedstream may exceed 700^{O} C. A sustained operation providing exhaust gas feedstream temperature that is in excess of 700^{O} C raises the adsorber operating temperature T_{ADS} above an upper temperature threshold, T_{UT}, leading to a substantially reduced efficiency, to a range as low 50% efficiency.

Referring now to Fig. 2, the method to control exhaust emissions from a compression-ignition engine having an exhaust aftertreatment system is shown in the form of a flowchart. An embodiment of the compression-ignition engine 5, controller 10, and exhaust aftertreatment system 22 has already been described herein in Fig. 1. The flowchart is preferably executed in the controller 10 during a preset loop cycle, typically each 6 milliseconds, during ongoing operation of the engine 5, using algorithms and calibrations, as described previously.

The method includes monitoring ongoing engine operation (Block 50), and determining an instantaneous engine operating point (Block 52). The method then determines the adsorber operating temperature T_{ADS} based upon the monitored operation of the engine 5 and input from the exhaust temperature sensor 40 (Block 54). The temperature of the NOx adsorber catalyst 38 is compared to the upper temperature threshold, T_{UT} (Block 56) which is determined based upon the characteristic temperature/efficiency curve shown in Fig. 3. When the temperature of the NOx adsorber catalyst 38 exceeds the upper temperature threshold, T_{UT}, the controller 10 acts to change engine operation by reducing the operating point (Block 60). The controller 10

preferably reduces the engine operating point by reducing the quantity of fuel delivered to the engine 5 through the plurality of fuel injectors 14. During each subsequent loop cycle, the controller 10 monitors the operating point and the NOx adsorber temperature, and continues to act to reduce the operating point (block 60) so long as the temperature of the NOx adsorber catalyst 38 exceeds the upper temperature threshold, T_{UT}.

Monitoring engine operation (Block 50) preferably comprises the controller 10 being operable to determine a mass of fuel delivered to the engine and engine rotational speed. The controller 10 determines the mass of fuel delivered by monitoring fuel flow through the plurality of fuel injectors 14, based upon commanded injector pulsewidth and calibration each of the plurality of fuel injectors. The controller 10 determines the engine rotational speed by monitoring engine crankshaft rotation using the crank speed sensor 12. The controller 10 is operable to determine the engine operating point (block 52) based upon engine speed as determined by input from the engine speed sensor 44, operator power demand as determined by the input from the accelerator pedal position sensor 32, and fuel delivery to the engine 5. One skilled in the art is able to calibrate a controller 10 to determine an engine operating point based upon engine speed, accelerator position, and fuel delivery, and also able to control fuel delivery for the compression-ignition engine 5.

The method determines temperature of the NOx adsorber catalyst 38, based upon the monitored engine conditions (Block 50), preferably using the adsorber operating temperature T_{ADS} and a catalyst temperature prediction model (not shown). The catalyst temperature prediction model is preferably executed in the controller 10 as a compilation of algorithms and calibrations, and is based upon the adsorber operating temperature T_{ADS} and ongoing engine operation. The catalyst temperature prediction model is created using a predetermined algorithmic model and associated calibration that is developed on representative pre-production engines and exhaust aftertreatment systems. The representative

pre-production engines and exhaust aftertreatment systems are tested over a range of engine operating points, using engine dynamometers. Temperatures are measured at predetermined locations in the exhaust aftertreatment system 22 and the NOx adsorber catalyst 38 in conjunction with the adsorber operating temperature T_{ADS}. The temperature measurements are captured and stored for use by a skilled calibrator to develop the calibration. The development, calibration and implementation of a catalyst temperature prediction model for use with an exhaust aftertreatment system attached to an engine is known to one skilled in the art.

The controller 10 preferably reduces the engine operating point (Block 60) by reducing the quantity of fuel delivered to the engine 5 through the plurality of fuel injectors 14. The reduction in the quantity of fuel delivered to the engine is preferably a minimal amount necessary to reduce the predicted temperature of the NOx adsorber catalyst. Determining an appropriate adjustment to fuel delivery is known one skilled in the art.

Although this is described as a method and control system to control exhaust emissions of a compression-ignition engine having a NOx adsorber catalyst, it is understood that alternate embodiments of this invention exist. Other configurations of the exhaust aftertreatment system may include different configurations of NOx adsorbers, oxidation catalysts, selective catalytic reduction (SCR) catalysts, and other elements available for emissions management for a compression-ignition engine. It is also understood that the invention does not rely upon a specific washcoat formulation for the NOx adsorber catalyst or the diesel particulate filter catalyst to operate correctly. Catalysts with combined functions, e.g. a catalyzed diesel particulate filter, or with different functions, are envisioned in this invention. The exhaust temperature sensor 40 operable to measure exhaust gas temperature may alternatively be placed in one of various other locations in the exhaust system, including, for example, at the inlet to the exhaust aftertreatment system 22, or

elsewhere in the exhaust feedstream. Alternatively, the system may rely entirely upon the temperature model to determine the temperatures of the exhaust gas and the aftertreatment system 22. The invention also encompasses all configurations of compression ignition engines, including various fuel injection schemes, piston/cylinder/head configurations, and cylinder configurations. It is also understood that the NOx efficiency levels stated hereinbefore represent the specific embodiment of the system; NOx efficiency levels for other engines and aftertreatment systems may be significantly different.

The invention has been described with specific reference to the preferred embodiments and modifications thereto. Further modifications and alterations may occur to others upon reading and understanding the specification. It is intended to include all such modifications and alterations insofar as they come within the scope of the invention.